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FUEL LUBRICITY—SURVEY OF THE LITERATURE

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by
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This report presents the findings of a literature survey on the general topic of fuel lubricity. The conclusions advanced by many investigators, based on their studies since the mid-1960's, are presented. From the survey the authors have drawn several conclusions which are also presented in the report. A list of 35 references and an annotated bibliography are provided.

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SUMMARY

Aircraft fuel system malfunctions attributable to the poor lubricating properties of on-board fuel first appeared in the mid-1960's. A consensus emerged with respect to the cause of the problem, i.e., the need for extraordinary refinery processing of poor quality crudes to meet fuel specification requirements. In particular, the increased supply of high-sulfur crude necessitated moderate to severe hydrotreating in order to reduce sulfur concentration to an acceptable level. Coincidently, hydrotreating also served to reduce/remove the polar, surface-active constituents of the fuel which are believed to provide improved lubricating characterstics.

The literature presents somewhat conflicting findings in regard to identification of the chemical species present in a fuel with "good" lubricity. High molecular weight aromatics, oxygen-, nitrogen-, and sulfur-containing compounds, and organic acids have been proposed as lubricity improvers, with varying degrees of agreement among investigators as to effectiveness. It is generally agreed that corrosion inhibitors of the MIL-I-25017 type do impart some measure of improvement in fuel lubricity, with effectiveness varying with inhibitor type and concentration. A 1974 Air Force study using a ball-on-cylinder machine showed that only one of eleven QPL additives examined noticeably improved the lubricity of a clay-treated JP-4 base fuel at the inhibitor's relative effective concentration (possibly a realistic field condition). Some improvement was observed with nine of the eleven inhibitors at the maximum allowable concentration (possibly an unrealistic field condition). More recent work by the Navy using a similar test apparatus and clay-treated JP-5 demonstrated some lubricity effect for most current QPL additives at their minimum effective concentration. However, at this concentration, the base fuel in most cases was not improved to the level considered necessary for a good lubricity fluid.

Laboratory techniques considered for the measurement of fuel lubricity have ranged from chemical procedures to bench-scale mechanical testers to full-scale pump tests. Most studies have concentrated on the evaluation and development of bench-scale devices, presumably because a direct indication of mechanical lubricating ability is obtained while avoiding the complexity and

expense of full-scale facilities. In the bench-scale category, the principal devices previously and/or currently under investigation include the ball-on-cylinder machine (BOCM), a derivation of the Furey BOCM, the Lucas dwell tester, four-ball testers, and various pin-on-disk machines. Although no single apparatus has been adopted as a "standard," the BOCM has received widespread acceptance in this country and the U.K. The BOCM is claimed to be sensitive to fuel lubricity differences, and to be correlatable with the Lucas dwell tester, the Bendix fuel system simulator, and a Vickers vane pump test.

The BOCM is designed so that changes may be easily imposed in machine geometry, metallurgy, temperature, speed, load, and test time. A major capability of the device is the moderate loading condition which can be utilized for fuel evaluations. This capability permits assessment of test fuel wear tendency without the occurrence of specimen (ball) scuffing, which masks any differences in lubricity between fuels.

It is concluded that the ball-on-cylinder machine is the most desirable technique of choice for present and future fuel lubricity studies. Although additional work will be required to refine the device in certain aspects, it is believed that the apparatus possesses the applicability and necessary requisites to become a "standard test' for use in fuel lubricity evaluations.

FOREWORD

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I. INTRODUCTION

As part of a program to evaluate the lubricity of synthetic crude-derived fuels, it was determined that a search of literature and existing data on fuel lubricity would be advantageous. Therefore, considerable effort was devoted to searching the technical literature for references to fuel lubricity. In addition, a bibliographic on-line machine, using key words, was employed to obtain a printout of possible applicable documents by title and author(s). From this printout, copies of the pertinent documents were sought.

Fuel lubricity problems began to receive considerable attention by various investigators after fuel control malfunctioning in a U.S. Air Force jet aircraft was diagnosed in 1965. After this malfunction, several cases of fuel pump failures and excessive wear of fuel-lubricated components began to appear in both commercial and armed services aircraft in Europe and the United States. As a result of the studies associated with these fuel-lubricity problems, a number of laboratory test machines have been employed, and the test results from some of these are presented in the literature. One of the major objectives of this phase of the program was to select a preferred test machine to evaluate the lubricity of various fluid fuels. For ease in presentation, the program discussion is categorized into the following:

(a) Nature of fuel lubricity problems.
(b) Role of additives and fuel dilution/blending on fuel lubricity.
(c) Fuel pumps.
(d) Evaluation of test techniques for fuel lubricity studies.

II. DISCUSSION

A. Nature of Fuel Lubricity Problem

After the aircraft field problems with lubricity[(1)*] in the mid-1960's, several studies were initiated using various test machines and techniques in an

* Superscript numbers in parentheses refer to the list of references at the end of this report.

attempt to better understand the mechanisms of fuel lubricity as well as establish a test to measure the lubricity of a fuel. Appeldoorn and Dukek[2] performed a literature survey on fuel lubricity and in 1967 reported that there was little agreement among investigators as to which fuel properties were important. Both physical and chemical properties of fuels including viscosity, pressure-viscosity, volatility, aromatics, sulfur, oxygenated compounds, and dissolved oxygen were said to influence friction and wear. On the other hand, the importance of each of these properties had been challenged and data shown to dispute claims of their effects on fuel lubricity. There was general agreement in the literature that antiwear and antifriction properties of additives such as organic phosphates and thiophosphates improve fuel lubricity although they adversely affect thermal stability. Metal deactivator and antioxidants have also been claimed to improve fuel lubricity but, as pointed out by Appeldoorn and Dukek[2], these data were less convincing. On the other hand, Johnston, in a discussion of this publication, feels that the Russian work[3,4], whose data are referenced, demonstrates a significant improving effect of conventional antioxidants on fuel lubricity.

Appeldoorn and Dukek[2] also present good background information on fuel pumps and fuel controls employed in the aircraft industry as well as some of the wear, seizure, and sticking problems associated with these equipment items. For their experimental study, they employed four tests: the Ryder gear test to measure tooth scuffing, a Vickers vane pump to measure wear and loss of volumetric efficiency, the four-ball wear tester to measure wear and scuff loads, and the Furey ball-on-cylinder test to measure friction wear and metallic content.[5] Of the test machines employed, they stated that the ball-on-cylinder test was found to be most useful. Based upon their study, they concluded the following:

(1) Poor performance of jet fuels in either friction or wear tests is more dependent on the traces of polar compounds in the fuel rather than viscosity or other physical properties.

(2) Marked differences can be observed in the lubricity of commercial fuels as determined by sensitive wear measurements or friction traces. These differences correlate with the field performance of fuels as observed by sticking or sluggish fuel controls or by high rates of pump wear.

(3) Lubricity differences among fuels are generally related to the degree of refining of fuels. The removal of chemically active species to upgrade the thermal stability of fuels is invariably associated with poorer lubricity. The active lubricity components removed in refining appear to be high molecular weight aromatics.

(4) Certain additives such as corrosion inhibitors have a marked effect on fuel lubricity. At very low concentrations, these additives reduce friction and wear, while at high concentrations they reduce gear scuffing; that is, they improve load-carrying capacity.

(5) Additives that act as lubricity improvers operate by different mechanisms. One class forms sacrificial films that reduce friction but increase wear, while another forms films that reduce both friction and wear.

> NOTE: In this case, friction is reduced but wear increases by rubbing away of the reacted materials, thus promoting further chemical reaction in the formation of a new film and so on, which is a continuing process. On the other hand, other additives appear to form lubricating films that reduce both friction and wear in the absence of the sacrificial chemically reacted material.

(6) A lubricity additive specifically tailored for high-temperature service rather than a corrosion inhibitor of the present type will be needed to provide both lubricity and thermal stability in a fuel for advanced aircraft such as the supersonic transport.

In continuing work, Appeldoorn and Tao[6] stated that heavy aromatic hydrocarbons are the most probable cause of good lubricity characteristics of petroleum oils; as little as 2 percent can greatly reduce the wear and friction and increase the load-carrying capacity of paraffins. They also point out that the mixture of heavy aromatics and paraffins is much improved over either component alone. In the absence of water and oxygen, condensed-ring heavy aromatics will allow scuffing at very low loads. This unusual behavior

is attributed to decomposition reaction at the rubbing surfaces rather than to oxidation or reaction with the metal. In 1960 Vere authored a paper[7] that referenced work by Appeldoorn, Goldman, and Tao which showed that the most likely wear mechanism between surfaces is corrosion primarily due to dissolved oxygen in the fuel with the process being accelerated by water. From the work of Appeldoorn, et al., Vere hypothesized that a polar compound forming a surface film should be a logical lubricity agent. Therefore, he designed a complementary program in the United Kingdom having as an objective to examine European fuels with regard to lubricity and to find a means of overcoming poor fuel lubricity problems based on his hypothesis.

During the period 1966-1968, there had been evidence from the field of a lack of fuel lubricity by at least four high-pressure piston-pump failures.[7] There was, according to Vere, a fuel pump modification using carbon faces on the sliding surfaces which would perform satisfactorily on all known jet fuels. This modification was assessed as being a possible solution to the problem. However, as a result of the first two pump failures which occurred using JP-4 fuel and nonmodified pumps, it was decided to investigate the lubricity of European fuels on similar equipment. A test machine with the capability of varying the metallurgy of the rubbing surfaces, and providing wear, friction, and metal contact measurements was sought. Three designs were considered and either rejected or accepted for reasons as follows:

(1) The four-ball machine was rejected because of its lack of sensitivity when using turbo-fuels and because of the difficulty in changing metallurgy of the balls.

(2) Modified Timken bearing rig was rejected due to its lack of sensitivity to small load changes and to difficulty in getting an adequate fuel supply on the rubbing surfaces.

(3) Pin and disk machine which was based on the ball-on-cylinder machine[5] was accepted because it could be readily adapted to the specific metallurgy of the rubbing surfaces of a piston-type fuel pump.

In using the pin and disk machine, Vere employed a carefully controlled test procedure. He[7] presented conclusions as follows:

(1) The active lubricity agents in jet fuels are highly polar compounds consisting of polynuclear aromatics, and fully saturated compounds containing sulfur of the thiahydrindane and thiadecalin type. Lubricity of jet fuel is satisfactory if it contains small quantities of these polar compounds. These may be present naturally in the fuel or may be added.

(2) If necessary, the addition of a highly polar compound can give the necessary lubricity to the fuel, for example, a corrosion inhibitor.

(3) Blending of hydrotreated and nonhydrotreated fuels gives satisfactory lubricity when only 10 percent of the fuel is nonhydrotreated. This could account for the nonappearance of this type of problem in the United States where 100 percent hydrotreated fuel is rarely marketed. In Europe, over 50 percent of jet fuel production is hydrotreated, and the rareness of problems in that area is no doubt due to natural dilution caused by the pickup of hydrotreated and nonhydrotreated fuels at different locations in a normal flight pattern.

(4) The lubricity test rig could be a useful guide to checking metallurgical combinations. It has correlated well with pumps of various configurations in the field.

Vere also presented possible future considerations as follows:

(1) If a control specification becomes necessary, it should be either a chemical test to measure the active lubricity constituents, or a mechanical rig test. Both of these are feasible, but the setting of a limit would be very different in either case.

(2) The chemical test has the advantage of cost, but depends on a fuller understanding of fuel and additive components. The mechanical test is apt to be expensive even if simplified, but must be very sensitive to be useful.

Further work by Vere was presented at an Advisory Group for Aerospace Research and Development (AGARD) Conference in 1971[8] and supplemented his earlier conclusions as follows:

(1) Up until this time, it had been considered that polynuclear aromatics were the most likely lubricity compounds in jet fuels, but analysis by high-resolution mass spectrometer showed that fully saturated heterocyclic sulfur compounds are the more active lubricity agent.

(2) The lubricity of batches of fuel from a specific process can vary from good to bad. The cause of this is unknown. Experience has shown that an occasional batch of fuel from all known processes may be suspect.

(3) Modifying the fuel pump to a carbon sleeve version overcomes the problem on all known fuels.

(4) The addition of a corrosion inhibitor at the rate of 12 ppm provides an effective lubricity agent.

(5) Where either pump modification or additive treatment has been tried in the field, no further problems have been reported.

Aird and Forgham[9] postulated that apparent wear in a failed fuel pump is scuffing wear caused by seizure following breakdown of the boundary lubrication. They stated that this view was quantitatively supported by Vere[7], but his work had not shown differences in normal wear rates for different fuels great enough to account for severe wear in a failed fuel pump. Therefore, they advanced the idea that the fuel property controlling this severe wear is the resistance to breakdown of the boundary lubricating film, and defined this as lubricity. They proposed that a boundary lubricating film is formed by adsorption of fuel constituents on metal surfaces and referenced experimental evidence[10,11] to support the existence of such adsorbed lubricant layers.

In selecting a relevant testing technique to show differences in lubricity of fuels, they stated that a test which can be easily correlated with data from actual pumps is essential. It is assumed that a complete prior knowledge of

the lubricity characteristics of fuel constituents is known for a chemical test to be effective. Therefore, the first step would necessarily be a mechanical test with the essential property under investigation being the resistance to breakdown of the boundary film. For this reason, Aird and Forgham[9] did not give wear testing further consideration. They proposed three techniques which they considered would show existence of boundary lubricating films for assessment. These were:

(1) Thin Film Viscosity - A technique based on work by Needs[10] and Askwith, et al.[11]

(2) Critical Temperature - A technique based on a concept by Blok[12], and experimental work by O'Donoghue, et al.[13]

(3) Dwell Test - A technique similar to the approaches made by Dacus, Coleman and Roess.[14] Further work has been carried out[11,15,16,17], but the technique has not previously been used to look for differences in lubricity between fluids which have essentially the same properties.

After preliminary experimental work, Aird and Forgham[9] decided the dwell test would be the most appropriate technique for continued testing. Based on their study, the following conclusions were presented:

(1) Large differences were found to exist in the lubricating properties of aircraft fuels manufactured to the same specification.

(2) A mechanical test was developed which can detect these differences, and results have correlated well with experience in the field. The test technique is particularly suitable because of its brevity and because of the small sample of fuel required per test. A test of this nature could be suitable for inclusion in a fuel specification.

(3) Fuels produced by hydrogen treatment seem more likely to be of low lubricity than fuels which have been otherwise treated. Poor lubricity fuels can, however, be produced by other treatments.

(4) With certain bearing metallurgy combinations, the use of a corrosion inhibitor improves fuel lubricity.

(5) Sulfur-containing compounds of certain types may be among those responsible for good lubricity.

(6) From their experience, it seemed that with the increased use of hydrotreatment as a method of refining, a greater number of low lubricity fuels will reach the market. For the future development of aircraft fuel systems, some standard type of fluid would be useful which would have a low lubricity. This would enable development and proof testing to be carried out on a fluid at least as bad as any which go into use. Before such a fluid can be produced, a better understanding of the "chemistry of lubricity" is necessary.

In a letter of comments on Aird and Forgham's paper[9], Bishop and Howells[18] question the validity of the cited pump proof tests using recirculatory test rigs since it was stated that recirculation of the test fuel improves its lubricating quality. Also, they do not believe the dwell test meets the necessary criteria for a fuel specification requirement because of poor repeatability, a lack of assessing the reproducibility of the test, and the excessive number of determinations to arrive at a reasonable average value for dwell number. They also question the claimed correlation between the dwell test and service results.

After the U.S. Army began considering the potential replacement of diesel fuel with aviation turbine fuel (because certain geographic areas that had been historically supplied by the U.S. Navy were required to change from diesel to JP-5 fuel), the Army pursued a universal fuel development program which sought certain fuel lubricity parameters. Responsibility for determining the suitability of fuels for use in Army diesel engines was assigned to the U.S. Army Materiel Development and Readiness Command which retained a private research and development company to evaluate friction and wear characteristics of selected jet engine and diesel engine fuels. Correlation of lubricity characteristics with the fuel chemical and physical properties was also part of the assigned effort. Therefore, Garabrant[19] employed a ball-on-cylinder machine (BOCM) and developed test conditions to evaluate friction and wear characteristics of eleven selected fuels. He also performed limited additional testing of some of the fuels with a Vickers vane pump and developed

test conditions for correlation purposes. The principal conclusions derived from this study were:

(1) Within the sample set selected, jet fuels and the arctic grade diesel fuel of West Coast origin result in higher wear levels than do these same fuels of East Coast origin. This is the result of processing (such as severe hydrogen treating), rather than geographical origin. The effect is not found with winter grade (DF-1) and the regular grade (DF-2) diesel fuels.

(2) Wear levels increase with increasing moisture levels in the ambient air.

(3) Fuels with nitrogen contents of 10 ppm or less have high wear levels. Fuels with nitrogen contents greater than 10 ppm have relatively low wear levels, and these wear levels are independent of their nitrogen content above 10 ppm. However, friction levels decrease, somewhat, with increasing nitrogen levels in the fuel.

(4) Fuels with sulfur concentrations below 0.10-0.12 percent have high wear levels. Fuels with sulfur concentrations about 0.12 percent have low levels, and their wear levels are not affected by the amount of sulfur above this value. However, high sulfur levels have a beneficial, but limited, effect upon the fuels' friction characteristics.

(5) Fuels with viscosities below 1.8-2.0 cSt at 100°F have higher wear rates than do fuels with viscosities at or above these levels. Increasing fuel viscosities above 2.0 cSt at 100°F does not effect further reduction in wear, but does reduce friction somewhat.

(6) The presence of "heavy ends" in the fuels reduces wear levels. Fuels with "95% distilled over" temperatures lower than 500°F had higher wear rates than did fuels with 95% off points over 500°F. Increasing the amount of "heavy ends" in the fuel reduces friction.

(7) A fuel with the following properties would minimize wear and friction levels:

(a) Organic nitrogen content of 10 ppm or greater.

(b) Organic sulfur levels in excess of 0.10 wt%.

(c) Viscosity greater than 2.0 cSt at 100°F.

(d) "95% distilled over" temperature of 500°F or higher.

(8) The fuels' physical and chemical properties are not independent of each other, but are interrelated:

(a) Fuels with low nitrogen levels also have low sulfur levels.

(b) Fuels with higher viscosities have higher "95% off" temperatures and higher final boiling points than do fuels of lower viscosity.

(9) The results of lubricity studies made with the Vickers vane pump test correlate with the results of the lubricity studies made with the ball-on-cylinder machine test. The results of the latter may be used to predict the results of the former.

(10) The Vickers vane pump test has higher precision than does the ball-on-cylinder machine test, but is less sensitive to differences in the lubricity of fuels than is the ball-on-cylinder machine test. While the ball-on-cylinder machine is the more sensitive screening device, the Vickers vane pump stress levels more closely approximate those found in diesel engine injectors and fuel transfer pumps.

Since conclusion (8a) above states that fuels with low nitrogen levels also have low sulfur levels, it is questioned how conclusions (3) and (4) are derived. It seems that it would be difficult to conclude whether the wear levels are a result of the nitrogen and/or sulfur concentrations in the fuel.

Seregin, et al.[20], using a friction tester which produces sliding friction and is claimed to give results that correlate well with the plunger wear in gas-turbine engine fuel pumps, investigated the lubricity of diesel fuels in relation to the fuel viscosity, the content and composition of sulfur compounds in the fuel, and the presence of naphthenic acids and finely dispersed free water.

Contrary to the results when using hydrotreated jet fuels, it was found that for diesel fuels the hydrotreating process, which normally removes surface-active heteroorganic compounds, did not give thorough removal of adsorption resins from the diesel fuel; therefore, the critical load did not decrease significantly. However, the corrosive sulfur compounds were thoroughly removed, and there was a very marked improvement in the wear index and hence the overall lubricity.

Krotky[21], in his treatise on properties of fuels used in the Czechoslovak aircraft industry, stated that lowering the level of aromatics, separation of sulfur compounds and polar substances, as well as separation of surface-active substances during the hydrogenation refining process, result in degradation of antifriction properties as compared to fuels produced by using other technological processes.

In the mid-1970's, the U.S. Navy began to experience fuel lubricity problems. Hang-up of a fuel control in an aircraft operating in the Mediterranean with subsequent failures of afterburner hydraulic-fuel pumps, both due to low lubricity fuel, were experienced. The problem fuels were from refineries outside the Continental United States. Therefore, the U.S. Navy initiated a program to determine the factors affecting fuel lubricity and developing ways of maintaining good fuel lubricity. In addition to inhouse work, the U.S. Navy is cooperating with the Coordinating Research Council Aviation Fuel Lubricity Group in evaluating the repeatability and reproducibility of the ball-on-cylinder machine. Grabel, using a ball-on-cylinder machine, undertook this task[22], as well as determining the lubricity of JP-5 fuels being produced at all refineries in the late 1970's.[23] Conclusions from the results of these studies were as follows:

(1) The BOCM can be used to distinguish between fuels with good and poor lubricity.

(2) The primary factor affecting the lubricity of jet fuels is the type and amount of nonhydrocarbon impurities in the fuel. Hydrotreating and clay filtration remove impurities from the fuel, thus making its lubricity worse.

(3) Changes in fuel composition within specification limits do not significantly affect the lubricity of JP-5.

(4) Organic acids and most types of nitrogen-containing impurities improve the lubricity of JP-5, while sulfur compounds and non-acid oxygen-containing impurities either have no effect or a slight detrimental effect on lubricity.

(5) Deoxygenation significantly improves the lubricity of fuels with poor lubricity; however, it has little or no effect on fuels that already have good lubricity.

(6) Most JP-5 fuels in 1977 contained a sufficient amount of naturally occurring nonhydrocarbon impurities to provide good lubricity.

(7) Approximately 42 percent of the JP-5 being produced in 1979 within CONUS had poor lubricity.

(8) Approximately 18 percent of the JP-5 being produced in 1979 outside CONUS had poor lubricity.

(9) The amount of poor lubricity fuel produced will increase in the future due to the increased use of crudes with high sulfur content.

(10) Fuel properties such as sulfur, aromatics, acidity, and olefin content cannot be used to predict fuel lubricity; however, a single fuel with low sulfur, aromatics, and acid contents generally will also have poor lubricity.

As a result of this work, three more conclusions pertaining to corrosion inhibitors, dilution, and additives were given and will be presented later in the report.

A list of recommendations as presented by Grabel in these references[22,23] were:

(1) The BOCM should continue to be used to evaluate fuels suspected of causing problems because of poor lubricity and to monitor fuel samples from the fleet to prevent future lubricity problems.

(2) Whenever possible, hydrotreated fuels should be mixed with nonhydrotreated fuels before use to prevent problems due to poor lubricity.

(3) Corrosion inhibitors should be added to fuels to improve their lubricity when necessary.

(4) The Navy should continue to cooperate with the Coordinating Research Council Aviation Fuel Lubricity Group in evaluating the repeatability and reproducibility of the BOCM.

(5) A lubricity requirement for JP-5 fuel should be established to prevent future lubricity-related problems.

(6) Periodic sampling of fuels from Navy and Marine Corps Air Stations should be done in order to monitor the lubricity of fuel actually being used in aircraft.

(7) New aircraft or fuel system components being developed should be required to operate satisfactorily on low lubricity fuel.

B. The Role of Corrosion Inhibitors, Fuel Dilution and Blending, Antiwear Agents, and Antioxidants and Anti-icing Additives on Fuel Lubricity

1. Corrosion Inhibitors

Vere[7,24] showed that of all fuel additives tested, only corrosion inhibitors produce a significant reduction in wear. In 1973 and 1974, the U.S. Air Force Aero Propulsion Laboratory studied the effects of corrosion inhibitors on jet fuel lubricity as well as other fuel properties.[1,25] Using a ball-on-cylinder machine, several conclusions were drawn and presented. A condensation of these is as follows:

(1) Several corrosion inhibitors on QPL-25017-9 were found to be effective as fuel lubricity agents in either JP-4 or JP-5 (Grabel[22], using a BOCM, also found that corrosion inhibitors improve the lubricity of JP-5, and effectiveness increases with increasing concentration in their allowable concentration range).

(2) Shell Sol 71, a solvent comparable to a calibration fluid used for the Lucas dwell meter, was found to be a suitable base fluid for lubricity evaluation of the corrosion inhibitors. Shell Sol 71 was superior to JP-4 or JP-5 for evaluating the effects of additives at very low concentrations.

(3) Preliminary results using the ball-on-cylinder lubricity test device revealed significant differences among the qualified corrosion inhibitors in regards to their effectiveness as fuel lubricity additives.

(4) Two inhibitors, DuPont AFA-1 and Nalco 5400-A, appeared to have no significant beneficial effect on the lubricity of a clay-treated JP-4 fuel at their relative effective or maximum allowable concentrations.

(5) The other nine inhibitors--Lubrizol 541, Tolad 244, Tolad 245, Apollo PRI-19, Unicor J, Nalco 5402, Conoco T-60, Hitec E-515, and DuPont DCI-4A--improved the lubricity of the fuel to varying degrees when tested at maximum allowable concentration.

(6) Only Hitec E-515 appeared to impart a measurable improvement in the lubricity of the clay-treated JP-4 fuel at its relative effective concentration.

Most of the corrosion inhibitors, with the exception of those containing phosphorous, were found to cause no measurable degradation of the thermal stability of the fuels. All of the corrosion-inhibited fuels decreased in filterability when sea water and a bare steel surface were simultaneously exposed to the fuel. However, the severity of the filtration problem varied for the different corrosion-inhibited fuels.

Grabel[26] showed that all corrosion inhibitors (12 ea) listed in QPL-25017-12, with the exception of two which were not available for testng, improved the lubricity of JP-5, but with significant differences in effectiveness. All of the corrosion inhibitors tested lowered the WSIM of JP-5 but to varying degrees. On the other hand, four of the additives combine effectiveness as lubricity improvers with minimal effect on WSIM.

2. Fuel Dilution and Blending

Grabel[22] showed that the addition of 10 to 20 percent of a good lubricity fuel with one having poor lubricity will usually produce a fuel with acceptable lubricity. Agnihotri, et al.[27], using a ball-on-cylinder machine, showed that blending of hydrotreated jet fuel with conventional refined fuels does not necessarily restore satisfactory lubricity. They point out that the degree of hydrotreatment and chemical treatment, along with the type of crude, are of importance. Vere[7] concluded that blending of only 10-percent hydrotreated with nonhydrotreated fuel will give satisfactory fuel lubricity. He also stated[24] that addition of a copper-sweetened fuel to experimental fuel improves lubricity until, at 30-percent dilution, there is no difference between the blend and a wholly copper-sweetened fuel. On the other hand, Brown[28] points out that it takes exceptionally good operation of a copper-sweetening unit to keep copper low enough in jet fuel to avoid failure in the thermal stability test.

3. Antiwear Agents

Misra, et al.[29,30], using a ZN-type machine originally designed for seizure load determinations of oils, which is suitably modified for low-viscosity fluids, evaluated lubricity of light mineral oil, aviation turbine fuels, diesel fuels, and blends of the two in suitable proportions to obtain diesel fuel of winter and subzero grades. These fuels blended with additives of complex esters or polymers showed that:

(1) Esters and polymers are effective lubricity improvers for aviation turbine fuels and diesel fuels, especially for diesel fuels of winter and subzero grades.

(2) Esters are comparatively more effective than polymers.

(3) Esters and polymers are superior to the conventional lubricity agents in view of their high solubility and absence of separation at extremely low temperatures. They are noncorrosive and, being ashless and nonsurfactant, do not affect water separometer and luminometer indices of the fuel.

(4) Excessive wear by fuel produced by some refineries can be reduced to a great extent by the addition of esters.

4. Antioxidants and Anti-icing Additives

Vere[7] showed that antioxidant additive in varying amounts in a severely hydrotreated experimental fuel had no effect on the wear rate in a pin and disk machine. Grabel[22] using a ball-on-cylinder machine concluded that neither antioxidants or anti-icing additives have an effect on lubricity of JP-5 in the allowable concentration range.

C. Fuel Pumps

Hamilton and Sparks[31] discussed the design and development of pumps for multifuel capability in the gas turbine engine. They review fuel lubricity data that have already been discussed in this document and conclude that the variable stroke piston pump which has been developed for the aircraft application has proven itself readily adaptable to new materials technology which allows it to pump any of the fuels so far encountered with satisfactory life and high volumetric efficiency. They point out that gear pump work has been much more limited, but has shown satisfactory running on low-lubricity fuels. They feel that aircraft experience has shown that both types of pumps will continue to find use in multifuel applications for the future for the aircraft industry as well as for other applications such as industrial and marine use.

Several pump test rigs have been employed[32], but there appears to be no standard test that can be employed or referenced for pump testing and correlation purposes. Evidently, some of the pump test rigs appear to be sen-

sitive to fuel lubricity while the capability of others in this respect is questionable. Since present pump development is directed toward use with low-lubricity fuels, a standard reference fuel appears to be needed.[32]

D. Evaluation of Test Techniques for Fuel Lubricity Studies

Since the latter part of the 1960's, the United Kingdom had several oil companies and fuel system component manufacturers performing investigations on the problems of fuel lubricity.[32] The Ministry of Aviation Supply (now Procurement Executive of the Ministry of Defence) decided to coordinate the investigations, first through a number of ad hoc meetings of interested parties and then in October 1969 by the formation of the Fuel Lubricity Panel. From then until the mid-1970's, considerable effort was spent toward being able to specify a lubricity parameter for aviation turbine fuel. Although a great deal was learned about lubricity, Vere, et al.[32] conceded that it was not possible to define a test that can accurately guarantee to control the lubricity of an aviation turbine fuel. At the 14th meeting of the Procurement Executive of the Ministry of Defence Fuel Lubricity Panel, it was decided that its activities to date should be reported. From the review of the lubricity activity by the editorial group, the following conclusions were drawn:

(1) Much time, money, and effort have been expended in the last 7 years in trying to find a method of effectively controlling the lubricity of aviation turbine fuels. Much has been learned about this subject and, as knowledge has been acquired, so the subject has become more complex.

(2) It is now known that a whole series of parameters affect the lubricity of a fuel.

(3) Certain chemical components have been identified as lubricity agents, but certainly not all chemical lubricity agents have been identified. For this reason, it is not considered possible to use a purely chemical approach to control the problem.

(4) Various rigs have been tried with varying degrees of success. The dwell tester, subjected to evaluation both in the U.K. and U.S. by the CRC, has

been shown in its present form to be unsuitable. Two wear test rigs show promise but have not been fully evaluated.

(5) Corrosion inhibitor additives appear to be effective on test rigs, and one has been successfully used in fuel systems for some years with success. Some of the additives have deleterious side effects, but work has shown that several do not. Engine evaluation is needed to clear these.

(6) Hardware has been shown to be critical, and a long-term solution would seem to be hardware that is not affected by a low-lubricity fuel. One such example is the Lucas all-carbon standard piston pump which has run successfully for a number of years without any reported lubricity failures.

(7) Present pump development is generally aimed at operation on low-lubricity fuel. For this, a standard reference fuel is needed. In the U.K., a subgroup of the Panel is working on the supply, storage, and availability of such a fuel.

(8) Guidance is sought from the Aviation Fuel Committee as to the future role of the Lubricity Panel.

In conclusion (4), it is stated that two wear test rigs show promise but have not been fully evaluated. From the review, it is fairly clear that one of these rigs is the ball-on-cylinder machine, but identification of the other rig is not so clear. After studying the review, it was decided that a pin and disk rig specifically designed by Esso Research Centre at Abingdon was the other rig.

From the studies reviewed above, it was shown that a chemical test approach showed some promise, but it was not possible to define a lubricity specification by chemical analysis.

Gureev, et al.[33], in a study of the lubricity of diesel fuels with respect to steels, employed an electrolytic cell having a two-phase electrolyte/hydrocarbon system. Their results were said to be in agreement with the concept of

a film mechanism of diesel fuel protective action and be usable as a basis for screening materials to be employed as additives to improve the protective properties of hydrotreated diesel fuels.

In the search for a solution to fuel lubricity problems, the Coordinating Research Council (CRC) of the U.S. and the MOD (PE) Fuel Lubricity Panel of the U.K. have cooperated closely. CRC has chosen the ball-on-cylinder machine for fuel lubricity studies. In a CRC Aviation Fuel Lubricity Group Meeting[34] (the first Group Meeting in 2 years), the members were most concerned with causes of wide variations in test results obtained by the various laboratories using the machine. Hopefully, steps are being taken to improve these results, such as better specimen heat treatment control, better control on ball contact location, better standardization of machines, etc.

Onion,[35] in a recent paper, describes briefly the different regimes of lubrication and goes on to examine boundary lubrication in greater detail. The asperity-interaction of boundary lubrication which is considered to have been disproven many times is attacked. From observations, Onion[35] offers an alternative hypothesis, "reaction film lubrication," where it is maintained the lubricating films are produced "in situ" by chemical reactions between the diesel fuel and the steel surfaces and that these reactions also cause chemical polishing of the surfaces. It is believed that this process explains many of the apparent anomalies in boundary lubrication and that it will be shown to be a common regime in other applications.

III. CONCLUSIONS

Based on this literature survey, the following conclusions are drawn:

- Lubricity is a complex problem, and it has been shown by various investigators that many parameters affect the lubricity of a given fuel.

- The ball-on-cylinder machine is the most desirable tester of choice for present fuel lubricity studies. Although future studies may show that other test machines or inspection techniques can better define and predict fuel lubricity expectations, the BOCM is the selected tester. Also,

it may be found that more than one test is needed to reliably predict fuel lubricity.

- Although most of the lubricity studies have been performed using aircraft jet engine fuels, extensive work needs to be performed on diesel fuels as well as new formulations of fuels that will become more commonly used for nonaeronautical power plants as well as aeronautical engines in the future (future fuels).

- Testing, with critical examination of the rubbing surfaces in the boundary lubrication regime, needs to be pursued. Especially of interest would be the wear mechanism and damage that happens early in a typical fuel lubricity test.

- Full-scale pump and fuel control tests need to be performed for correlation with the ball-on-cylinder machine tests.

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6. Appeldoorn, J.K. and Tao, F.F., "The Lubricity Characteristics of Heavy Aromatics," Wear, Vol. 12, pp 117-130, 1968.

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    This is a short communication that shows from limited studies using the ball-on-cylinder technique that blending of hydrotreated fuel with conventional fuels is not a satisfactory cure for restoration of lubricity to jet fuel. (5 references listed).

2. Aird, R.T. and Forgham, S.L., "The Lubricating Quality of Aviation Fuels," Wear, Vol. 18, pp 361-380, 1971.

This publication states that aviation fuels from various sources have shown differences in lubricating ability and presents details of incidents that have occurred as a result of poor fuel lubricity. A mechanical test was developed (dwell test) based on the assumption that the resistance to breakdown of the boundary lubricating film depends upon the tenacity of certain fuel constituents adsorbed on the bearing surfaces. Results are shown to correlate well with service experience including pump performance using fuel containing a strongly adsorbing polar additive. (17 references listed).

3. Appeldoorn, J.K. and Dukek, W.G., "Lubricity of Jet Fuels," SAE Trans., Vol. 75, No. 3, pp 428-440, 1967.

This paper presents considerable background information on failures of fuel-lubricated components of aircraft fuel systems in the mid-1960's. They show that poor performance of some high-purity jet fuels appears to be related to polar compounds rather than physical or chemical properties in the fuel. Surface-active additives such as corrosion inhibitors are shown to greatly improve lubricity. Highly refined fuels developed to meet thermal stability or purity standards were shown to generally have poor lubricity. (18 references listed).

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Oxygen and moisture are shown to cause a significant increase in friction and wear under nonscuffing conditions. In certain cases, wear in humid air is destructive, but can be entirely eliminated by blanketing the system in dry nitrogen. This wear effect of air is entirely reversible, occurs with most metallurgies and lubricant types, and may be controlled by incorporating suitable additives in the oil. Various wear mechanisms have been examined to explain the

experimental results; the most satisfactory is a simple corrosive wear phenomenon, involving the formation and rubbing away of metal oxides. (26 references listed).

5. Appeldoorn, J.K. and Tao, F.F., "The Lubricity Characteristics of Heavy Aromatics," Wear, Vol. 12, pp 117-130, 1968.

Friction and wear properties were determined in several different test apparatus in which it was shown that heavy aromatic hydrocarbons are the most probable cause of the good lubricating characteristics of petroleum oils. As little as 2 percent can greatly reduce wear and friction and increase the load-carrying capacity of paraffins. These mixtures of heavy aromatics and paraffins are much better than either component alone. Condensed-ring heavy aromatics have a second unusual behavior; in the absence of water and oxygen, they will scuff at very low loads. The unusual behavior of the heavy aromatics is attributed to a little-understood decomposition reaction at the rubbing surface and not to oxidation or reaction with the metal. (5 references listed).

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This paper studies the influence of surface active compounds on lubrication of a slow-running four-ball machine. The lubricants are pure paraffins, mainly hexadecane, and the additives long-chain acids, amines, and alcohols. It was found that the oil film was markedly influenced by the additive and a sharp peak in the curve of scuffing load against chain length was found when the additive and the carrier were of the same chain length and shape. The surface viscosities were measured by a falling plate viscometer and the same peak was found when complete matching of the chain length occurred. These results lend support to the existence of the long-range forces. The Langmuir isotherm gives an explanation of the failure of lubrication, which leads to the seizure of the surfaces. This

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This report reviews the state-of-the-art of boundary lubrication and presents the prospects of such improvements in the lubrication of highly-loaded bearings as virtually to eliminate bearing failures and the need to relubricate machinery in the field. It includes a survey of instances of anomalously successful boundary lubrication and of mathematical models which might explain the low wear observed. These models are shown to be inadequate and some steps are taken to complete them. It is shown that 27 of the 28 anomalies are explained by the expanded models. A plan for applying this knowledge to design practices is outlined. (Extensive bibliography listed).

8. Brown, K.M., "Treating Jet Fuel to Meet Specs," Hydrocarbon Processing, pp 69-74, February 1973.

Since some jet fuel specifications have little or no bearing upon fuel performance, this is a review of how jet fuel quality is influenced by the processes of Doctor sweetening, copper sweetening, and the Merox process. (2 references listed).

9. Furey, M.J., "Metallic Contact and Friction Between Sliding Surfaces," ASLE Trans., Vol. 4, pp 1-11, 1961.

Development and use of a new device to study metallic contact and friction between sliding lubricated surfaces is discussed. The device consists basically of a fixed metal ball loaded against a rotating cylinder. The extent of metallic contact is determined by

measuring both the instantaneous and average electrical resistance between the two surfaces, and friction between the ball and cylinder is recorded simultaneously. (14 references listed).

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This report presents data obtained for the U.S. Army in its consideration of the replacement of diesel fuels with aviation turbine fuels, and also its pursuit in developing a universal middle distillate fuel in which certain lubricity parameters are sought. The wear and friction characteristics of eleven selected aviation turbine and diesel fuels were evaluated with the aid of the ball-on-cylinder machine. Limited additional testing of some of the fuels was done with the aid of the Vickers vane pump. Fuel nitrogen and sulfur levels, as well as back end volatilities and viscosities, are factors in wear phenomena. Relative humidity of the ambient air, or water content of the fuels, has a significant effect upon the fuels' lubricity properties. Wear phenomena observed with the ball-on-cylinder machine and the Vickers vane pump are correlatable. (7 references listed).

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This report gives some history on lubricity of JP-5 as experienced by the U.S. Navy. Using a ball-on-cylinder machine and an Emcee water separometer, the effects of corrosion inhibitors on lubricity and WSIM, respectively, of JP-5 are investigated. (3 references listed).

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This report summarizes the results of a program to determine the lubricity of JP-5 fuels in use at the time it was published. It is

also intended to serve as an aid in future decisions about lubricity and fuel specifications and additives. (4 references listed).

13. Grabel, L., "Lubricity Properties of High Temperature Jet Fuel," NAPC Report No. NAPTC-PE-112, August 1977.

This report discusses the initiation of a program by the U.S. Navy in 1975 toward a better understanding of the causes of fuel-lubricity problems and a means of solving the problems if they do occur. The ball-on-cylinder machine was employed for this work in an effort to determine the factors that are of importance in fuel lubricity. (11 references listed).

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A laboratory test device for rating the lubricity of jet fuels was developed and is discussed in this paper. The device gives a simulation of the conditions under which fuel is employed as a lubricant in the rocker unit of the fuel pump/control. A criterion is proposed for evaluating fuel lubricity. (9 references listed).

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This work consisted of a study of the lubricity of diesel fuels with respect to steel and an investigation of the factors involved in downgrading of protective properties when fuels are hydrotreated. Fuel lubricity was evaluated on the basis of the cathode current generated by the part of an electrode located under a film of electrolyte and above the interface in an electrolyte/fuel system. (5 references listed).

16. Hamilton, L.P. and Sparks, B.E., "Pumps for Low Lubricity and Corrosive Fuels," ASME Paper No. 75-GT-102, March 1975.

One of the advantages of the gas turbine is that it can burn almost any kind of flammable liquid. The aim of the fuel system engineer must therefore be to provide equipment which can pump and meter any fuel which is acceptable to the engine, without limiting the engine performance, life, or reliability. The reasons why the authors believe this aim to be of particular importance at the present time, and the kind of engine to which it is most relevant, are outlined. The principal topic, the design and development of pumps able to achieve this "multifuel capability," is also discussed. (2 references listed).

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This paper focuses on antifriction properties, lubricating quality of fuels, and their corrosiveness. Those parameters of fuels for aircraft turbine engines which affect the functioning of the fuels and control systems are discussed. The potential for contamination by mechanical impurities, water, and microorganisms are examined. The reasons for increasing demand for high-purity fuels are cited.

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Lubricity evaluation, using a friction tester, for a number of commercial jet fuel samples in various grades is presented. The effects of a number of corrosion inhibitors on fuel lubricity are also shown. (10 references listed).

19. Martel, C.R., Bradley, R.P., McCoy, J.R., and Petrarca, J., Jr., "Aircraft Turbine Engine Fuel Corrosion Inhibitors and Their Effects on Fuel Properties," AFAPL-TR-74-20, July 1974.

This report discusses the effects of corrosion inhibitors on the thermal stability, filterability, and lubricity of aircraft turbine engine fuels. The corrosion inhibitors were found to affect the thermal stability, filterability, and lubricity of fuels differently. For example, some of the corrosion inhibitors gave no measurable improvement in the lubricity of the fuel while others were quite effective, using the Furey ball-on-cylinder test device. Similarly, most of the corrosion inhibitors caused no measurable degradation of the thermal stability of the fuels while others did. All of the corrosion inhibitors were found to decrease the filterability of the fuel when sea water and a bare steel surface were simultaneously exposed to the fuel containing the corrosion inhibitors. However, the severity of the filtration problem varied among the corrosion inhibitors. (11 references listed).

20. Misra, A.K., Mehrotra, A.K., Srivastava, R.D., and Nandy, A.N., "Complex Esters as Antiwear Agents," Wear, Vol. 26, pp 229-237, 1973.

Diol-centered complex esters using diethylene glycol, 1,3-butane diol, neopentyl glycol, polyethylene glycol (molecular weight 200-1000), 1-phenoxy 2,3 propane diol as centered diols and sebacic acid as dibasic acid with outer monohydric alcohols as 2-ethyl hexanol, 1-benzyloxy propanol-2 and methyl digol were prepared and assessed as antiwear agents in aviation turbine fuels, diesel fuels, and light mineral oil. These types of complex esters, in general, were found to be effective antiwear agents. (23 references listed).

21. Misra, A.K., Mehrotra, A.K., and Srivastava, R.D., "Fuels of Improved Lubricity," Indian Journal of Technology, Vol. 13, pp 406-410, September 1975.

The influence of some high molecular weight polymers and esters on the lubricity of various fuels (ATF and diesel) produced in India has been studied. In general, all the esters and polymers used brought about considerable improvement in lubricity, esters being more effective than polymers. (34 references listed).

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A pin-on-disk machine was used to study relative frictional and wear characteristics of several fuels which might be employed in the Army multifuel truck engines. A summary of the wear volume and average coefficient of friction for each fuel is presented.

23. Onion, G., "Reaction Film Lubrication," Chartered Mechanical Engineer, July 1979.

The author describes briefly the different regimes of lubrication and explains boundary lubrication in greater detail. He attacks the asperity-interaction view of boundary lubrication which he considers to have been disproved many times. From his observations of lubricated surfaces, mainly on components of diesel fuel injection systems, he offers an alternative hypothesis, "reaction film lubrication." He maintains that lubricating films are produced "in situ" by chemical reactions between the diesel fuel and the steel surfaces and that these reactions also cause chemical polishing of the surfaces. He believes that this process explains many of the apparent anomalies in boundary lubrication and that it will be shown to be a common regime in other applications. (6 references listed).

24. Petrarca, J., Jr., "Lubricity of Jet A-1 and JP-4 Fuels," AFAPL-TR-74-15, NTIS Report No. AD 784772, June 1974.

This report describes the evaluation of an instrument that gives an indication of the lubricity of a fuel and of the results from testing Jet A-1 and JP-4 fuels with the device. The instrument is the Furey ball-on-cylinder. The preliminary investigation dealt with establishing the repeatability and reproducibility of the rig on pure hydrocarbons and Jet A-1 fuels. Also, the results from the Jet A-1 fuels served as the basis for a direct comparison between the wear scar diameter from the ball-on-cylinder and the coefficient of friction from the Bendix-CRC lubricity simulator. (10 references listed).

25. Petrarca, J., Jr., "Aviation Turbine Fuel Lubricity Evaluation of Corrosion Inhibitors," AFAPL-TR-75-47, September 1975.

This report describes the evaluation of the effectiveness of corrosion inhibitors as fuel lubricity agents. The study was conducted with the Furey ball-on-cylinder machine. In the study, the eleven corrosion inhibitors were evaluated as lubricity agents in three base fluids, at various concentrations, and at the two base fluid temperatures of 75° and 150°F. (10 references listed).

26. Poole, W. and Sullivan, J.L., "The Wear of Aluminum-Bronze on Steel in the Presence of Aviation Fuel," ASLE Trans., Vol. 22, No. 2, pp 154-161, April 1979.

A study was made of the action of a commercially-available corrosion inhibitor added to hydrofined aviation fuels in reducing the wear of aluminum bronze sliding on KE 180, 13 percent chromium steel. From measurements of friction and wear and an extensive examination of surfaces using Auger electron spectroscopy, a surface model was proposed which sheds light on the mechanism of wear protection.

27. Seregin, E.P., Gureev, A.A., Bugai, V.T., Makarov, A.A., Sarantidi, P.G., and Skovorodin, G.B., "Lubricity of Diesel Fuels," Chemistry and Technology of Fuels and Oils, Vol. 11, No. 5-6, pp 360-363, May-June 1975. (Translated from Khim. i Tekhnol. Topliv i Masel, No. 5, pp 21-24, May 1975).

In this study, the lubricity of diesel fuels in relation to fuel viscosity, the content and composition of sulfur compounds in the fuel, and the presence of naphthenic acids and finely dispersed free water was determined. The experiments employed a friction tester which produces sliding friction and gives results that are claimed to correlate quite well with the plunger wear in gas-turbine engine fuel pumps in tests on nonadditive fuels. (7 references listed).

28. Tao, F.F. and Appeldoorn, J.K., "The Ball-on-Cylinder Test for Evaluating Jet Fuel Lubricity," ASLE Trans., Vol. 11, pp 345-352, 1968.

In this paper, the emphasis is on the advantages of using the ball-on-cylinder machine for evaluating jet fuel lubricity. The machine can operate at low enough loads so that subtle differences in fuel quality can be detected. Examples are given of the effect of refining, the differences in additive action, the importance of test atmosphere, and the influence of temperature. Other test methods appear to be too severe for all-around fuels testing, and some of these test methods are discussed. (7 references listed).

29. Thompson, J.S., "Aircraft Fuel Pumps--Where We're At (A Review of Some Problems and Their Current Solutions)," ASME Paper No. 78-GT-10, April 1978.

European-designed tank-mounted boost pumps, the thermal diffuser, engine-driven backing pumps and gear pumps have all changed, and improved, over the last few years. This paper outlines the reasons for the changes, the problems they are designed to overcome, and the efficiency of the solutions offered.

30. Vere, R.A., "Lubricity of Aviation Turbine Fuels," SAE Trans., Vol. 78, Section 4, pp 2237-2245, 1969.

A laboratory test rig was used to evaluate European jet fuels for lubricity and showed that the more highly refined fuels are poorer in lubricity than the conventionally refined fuels. The addition of

a surface-active additive such as a corrosion inhibitor improves lubricity. Experience of additive addition to fuel for aircraft of two European airlines in 1968 confirmed laboratory results. Highly polar compounds extracted from conventionally treated fuels significantly improved lubricity when added to highly refined fuels. The blending of 10 to 20 percent of a conventionally treated fuel to a highly refined fuel improves lubricity to the level of the conventional fuel. (3 references listed).

31. Vere, R.A., "Dilution Restores Lubricity to Hydrotreated Jet Fuels," SAE Journal, Vol. 78, No. 4, April 1970.

This article states that highly refined jet fuels lack lubricity and can cause fuel pump failure. By use of pin-and-disk machine, it has been shown that lubricity and wear resistance of a highly refined or hydrotreated jet fuel can be restored by proper blending with a chemically treated fuel. (2 references listed).

32. Vere, R.A., "Aviation Fuel Lubricity," Advisory Group for Aerospace Research and Development Conference Proceedings," AGARD-CP-84-71, pp 11-1 through 11-13, 1971.

Fuel pump failures have occurred in Europe during the last 3 years for which the fuel has been considered to be in part responsible. A laboratory test rig has been developed which has evaluated European jet fuels with regard to lubricity. This has shown differences in the lubricity levels of different fuels. Active lubricity agents have been identified as fully saturated heterocyclic compounds and polynuclear aromatics. The addition of a surface-active additive such as a corrosion inhibitor also significantly improves lubricity but can incur conductivity problems in the field due to its synergistic effects with antistatic additive. From a series of field incidents, a pattern is emerging. Modification of the fuel pump hardware is the best solution to the problem. The addition of a corrosion inhibitor to the fuel has been shown to alleviate the problem. (4 references listed).

33. Vere, R.A., Ashwith, T.C., and Hardy, P.J. (Editors), "Lubricity of Aviation Turbine Fuels," Second Report of Work and Findings of the MOD (PF) Fuel Lubricity Panel, Esso Research Centre, Abingdon, REF: AX/395/014, January 1976.

Since 1970, the Ministry of Defence (Procurement Executive) Fuel Lubricity Panel has expended considerable time in an effort to produce an effective and realistic test to be able to specify a lubricity parameter for an aviation turbine fuel. Although a great amount has been learned about lubricity, it has been shown to be very complex and remains not possible to define a test that can accurately guarantee control of the lubricity of an aviation turbine fuel. At the 14th meeting of the Fuel Lubricity Panel it was decided that in advance of further studies, a report of its activities to date should be written. The first step was for each panel member to prepare a summary of his own studies. From these contributions, this report, which constitutes a review of lubricity activity as seen by the editorial group, was prepared and printed.

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